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COLOUR RECONNECTIONS IN QUARK AND GLUON JETS IN HERWIG 7*

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Major event generators deviate significantly in their description of quark and gluon initiated jets. The modelling of these is particularly sensitive to the colour reconnection model used in the cluster hadronization model in the event generator Herwig. However, up to now, observables sensitive to the light flavour of jets have not been widely used in the construction and tuning of event generators. The scheme used in Herwig and changes within it are investigated using observables in e^+e^- and pp collisions, which are expected to discriminate quark and gluon jets.

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1. Introduction

Experimental analyses at colliders like the LHC rely on efficient suppression of background processes, QCD jet production often being an important one. Looking closer at the typical signal processes, associated jets are often quark-initiated at lowest order. On the other hand, QCD $2 \to 2$ scattering receives a significant contribution from gluon initiated jets. This makes distinguishing quark and gluon jets a vital experimental tool. It is thus crucial to understand the modelling of quark and gluon jets in Monte Carlo event generators. As previous studies [1, 2] pointed out, there are large discrepancies in the description of these between major event generators, so that it seems desirable to directly use information on the nature of light jets in

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developing and tuning the corresponding models. See [1] for a discussion on a rigorous definition of a gluon jet. With this in mind, the definitions used in the respective measurements have to be adopted when comparing to corrected data. In this paper, changes to the hadronization model used in Herwig 7 [3, 4] are investigated, considering observables sensitive to the quark and gluon nature of jets.

In Section 2, the choice of observables is motivated. Afterwards, in Section 3, the default hadronization model in Herwig 7.0 will be described briefly, and the changes investigated here are detailed. Finally, in Section 4, results of the changed colour reconnection model compared to data are presented. The conclusions are summarised in Section 5.

2. Differences of quark and gluon jets

Looking at the perturbative part of event generation, one can form a first expectation of what observables are potentially useful in distinguishing quark and gluon jets. The dominant process in the shower will be gluon emissions from the quark or gluon. This will be governed by the respective colour factors, $C_{\mathrm{A}} = 3$ for the emission from gluons and $C_{\mathrm{F}} = \frac{4}{3}$ for the emissions from quark lines. Thus, a gluon jet is expected to contain on average more radiation than a quark jet by some sensible measure. One, therefore, naturally considers observables like the (charged) multiplicity of particles within the jet and jet width related observables.

3. Hadronization in Herwig 7

Although perturbatively, there is a clear expectation on the different behaviour of quark and gluon jets as set out in the previous section, the finally expected distributions are subject to the additional non-perturbative formation of hadrons. This is taken into account in event generators by means of hadronization models in order to allow for a meaningful comparison of generated events to experimental data.

For simplicity, first consider the case of $e^+e^- \to$ hadrons. The cluster hadronization model implemented in Herwig is based on the idea of colour-preconfinement: After the parton shower has terminated, remaining gluons are split non-perturbatively into quark–antiquark pairs. The partonic state then consists of colour connected quarks, which form colour singlet clusters as shown in figure 1. The property of preconfinement is observed for hadronic clusters in e^+e^- collisions [5], where the distribution of cluster masses is independent of the energy scale considered, peaking at low energies and falling off rapidly for increasing energy. It is expected to hold for planar diagrams with corrections suppressed by powers of $1/N_{\mathrm{c}}^2$. A hadronic final state can then be obtained by subsequently decaying the clusters into hadrons.

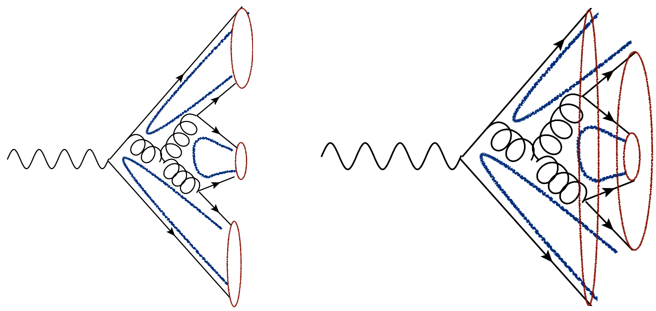

Fig. 1. (Colour on-line) The sample final state in e^+e^- collision with dominant colour flow (grey/blue lines) and formed clusters (black/red blobs) before (left) and after (right) colour reconnection in the default model.

The picture changes if one considers hadron–hadron collisions. There, coloured beam remnants are connected to final-state partons in a non-perturbative way, leading to a breakdown of colour-preconfinement. It is, however, possible to recover it by allowing colour reconnections beyond the planar diagrams through a suitable algorithm [6], of which the simplest version will just take all partons in random order, and try to reconnect them to another parton if the mass of the new cluster is smaller then the mass of the current cluster the parton belongs to, accepting the reconnection with probability p_{reco}. This is a free parameter of the model to be tuned to suitable data. Its value in the default tune of Herwig 7.0 is $p_{\mathrm{reco}} = 0.4276$, using the MMHT2014 LO parton distribution function. The model described above will be referred to as the default model, to distinguish it from the changes explained below.

It was noticed [1] that the discrimination power between quark and gluon initiated jets of certain observables as predicted by Herwig strongly depends on this part of the hadronization model. In particular, in the default set-up described above, the Herwig predicts much lower discrimination power for all observables considered in [1] than other generators. Contrary, if the colour reconnection is turned off completely, higher discrimination is reached, rendering the Herwig prediction similar to the other event generators considered. Note, however, that colour reconnection is needed to fit underlying event and minimum bias data [6] and, thus, turning off colour reconnections is not a viable model assuming universality between lepton and hadron collisions.

Seeking for an intermediate solution, allowing to fit soft physics data as well as consistently describing gluon jets, one might notice that in the default model, it is possible for a gluon jet to become a colour singlet after reconnection (see figure 1), disconnecting it completely from the rest of the event.

A simple extension of the default model is, therefore, to veto exactly this kind of reconnection. The option to do so is implemented in Herwig 7.1. In the following, this will be referred to as the modified model. One might expect that the predictions from Herwig look more similar to other generators after this adjustment, however what one really aims for is of course an accurate description of measured data, which is investigated in the following section.

4. Results

Observables sensitive to the quark and gluon nature of jets have been measured at LEP for example by the OPAL Collaboration [7] and more recently, in pp collisions at the LHC by ATLAS [8]. Results from [9] and [10] have also been considered and found compatible with the conclusion drawn later, the analyses presented here are found to be most sensitive to the changes in the modified model.

The first analysis by OPAL considers gluon jets defined by the boost algorithm which is described in detail in [7]. The observable found to be most sensitive here is the multiplicity of charged particles in the jet. Shown in figure 2 are the predictions from Herwig 7.0 with different values of $p_{\rm reco}$ and from Herwig++ 2.7, both using the default model. Additionally, the default model but with $p_{\rm reco} = 0$, which is equivalent to turning off colour reconnection, is displayed. For all other values of $p_{\rm reco}$, one observes a general discrepancy between data and prediction. In particular, a preference of an

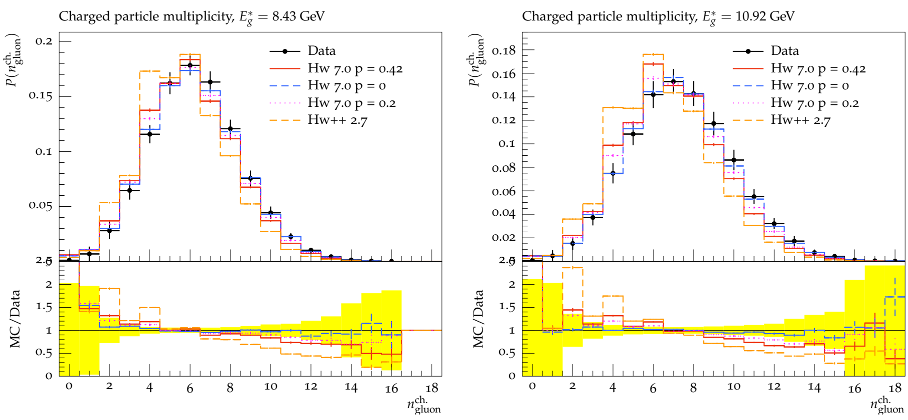

Fig. 2. Distribution of charged particles in gluon jets defined by the boost algorithm, at different energy scales E_g^* of the jet. Data taken from [7]. Shown are predictions from Herwig 7 (Hw 7.0) with different values of $p_{\rm reco}$, $p_{\rm reco} = 0.42$ (Herwig 7.0 default), $p_{\rm reco} = 0.2$, $p_{\rm reco} = 0$ (no reconnection) and from Herwig++ 2.7 (Hw++ 2.7), all using the default model.

even number of charged particles in gluon jets, which is not present in the data, can be seen. This behaviour can be understood as a consequence of the isolation of the gluon jet from the rest of the event (see *e.g.* figure 1, right). Such jets will inherit the overall charge of 0 from the gluon, implying an equal number of positively and negatively charged particles, and thus an even number of charged particles.

Figure 3 shows the same data as figure 2, but using the modified model in the simulation. The distributions obtained from this are mostly independent of p_{reco}. The seemingly unphysical features of the default model have disappeared due to the change in the model, and the data are described well over the whole range.

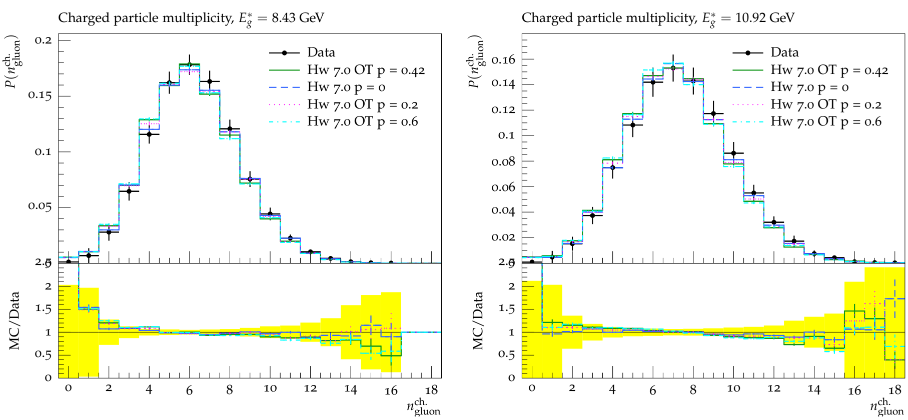

Fig. 3. Distribution of charged particles in gluon jets defined by the boost algorithm, at different energy scales E_g^* of the jet. Data taken from [7]. Shown are predictions from Herwig 7 (Hw 7.0) with different values of p_{reco}, $p_{\mathrm{reco}} = 0.42$ (Herwig 7.0 default), $p_{\mathrm{reco}} = 0.2$, $p_{\mathrm{reco}} = 0.6$, $p_{\mathrm{reco}} = 0$ (no reconnection), all using the modified model with special octet treatment (OT).

It can be concluded from this discussion that the modified model is improving the modelling of gluon jets at least in e^+e^- collisions. As a next step, observables in hadron collisions can be considered.

Sensitivity to the nature of jets is provided, for example, by the comparisons of central and more forward jets in [8]. The number of charged particles in these two jet regions is expected to differ according to the relative rates of quarks and gluons expected therein. Thus, the averaged difference of the number of charged particles gives a measure of the difference between quark and gluon jets.

The predictions from Herwig 7.0 are shown in figure 4, together with the prediction for the sum of the number of charged particles in these two jets. The description of the data is somewhat improved by the modified model in comparison to the default model, at least as far as the difference between the central and forward jet is concerned. However, quantitatively this depends largely on specific choices in the parton shower and the corresponding tuning strategies, leading to some offset constant in p_T for the total number of charged particles in some cases. However, agreement within less than 10% is reached in all cases for the total number of charged particles.

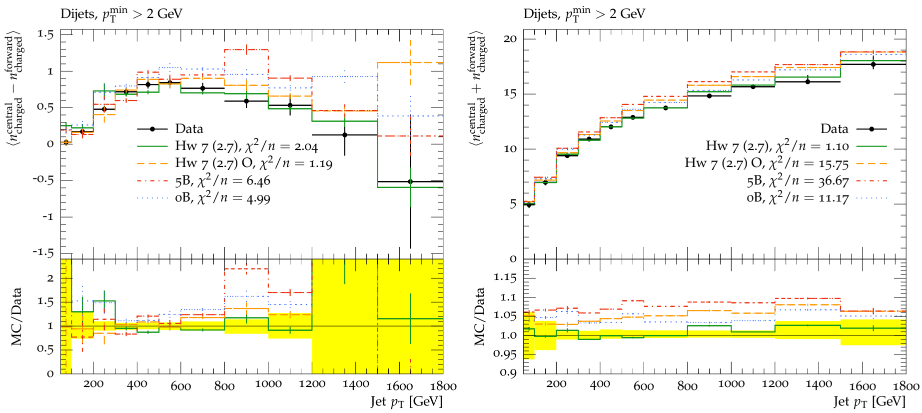

Fig. 4. (Colour on-line) Difference and sum of the average number of charged particles in the most central and the next more forward jet. Data taken from [8]. Shown are predictions from Herwig with different tuning strategies, with the modified model (dashed/orange, dash-dotted/red, dotted/blue) and with the default model (solid/green).

5. Summary and outlook

It has been shown how the modelling of gluon jets in e^+e^- collisions can be systematically improved by simple and physically motivated changes to the colour reconnection model used in Herwig. Even on a qualitative level, improvement is found in this case. A new tune of the hadronization model using this information and the corresponding final conclusion for the case of hadron collisions will be presented elsewhere.

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